Corps Water Management System
Decision Support Modeling

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Abstract: The U.S. Army Corps of Engineers has developed a comprehensive data acquisition and hydrologic modeling system for real time decision support of water control operations. This system, known as the "Corps Water Management System", or CWMS, has been implemented at Corps offices throughout the United States. CWMS retrieves precipitation, river stage, gate settings and other data from field sensors, and validates, transforms and stores those measurements in a database. The measurements are used for calibration and adjustment of hydrologic and hydraulic models to reflect current conditions. Hydrologic and hydraulic simulation models are executed utilizing observed gauged precipitation and flow data, combined with Quantitative Precipitation Forecasts (QPF) or other future precipitation scenarios, to evaluate operation plans for reservoirs and other control structures, and view and compare hydraulic and economic impacts for various "what if?" scenarios. The lessons learned from the initial deployment of CWMS Version 1.0 to Corps Water Control field offices are addressed. In February of 2003, Version 1.1 of CWMS was released. Improvements in this version, as well as planned enhancements of CWMS, are discussed.

INTRODUCTION

The U.S. Army Corps of Engineers has developed the "Corps Water Management System", or CWMS, a comprehensive integrated system to support the informational needs for Corps water control decisions in its operations of over 700 reservoir and lock-and-dam projects. CWMS is a nationwide project that incorporates the acquisition, transformation, verification, storage, display, analysis and dissemination of data and information to carry out the water control mission of the Corps. Typically this information includes hydrologic, meteorological, water quality, and project data and information. The system automatically collects data continuously from thousands of sensors throughout the nation, as well as spatial satellite and radar imagery, and graphical and text products. The project substantially upgrades the Corps's computer and related hardware, its procurement and adaptation of Commercial Off-The-Shelf (COTS) software, and its development and maintenance of acquisition, visualization and modeling software in support of this effort.

Prior to CWMS, water management decisions in the Corps were supported by the "Water Control Data System", or WCDS (USACE, 1995), which evolved over the period 1975 to 1990. The WCDS was comprised of dedicated mini-computers, data acquisition and communications hardware. Although guided by Corps policy, the WCDS was not a centrally planned and developed system, except for computer hardware. Some data processing programs were developed and fielded Corps-wide; others were developed and used regionally or in individual offices. From a national view, it was an assortment of individual systems that were locally maintained, managed and supported. The system was inconsistent in the level of performance and capacity across the Corps, and simulation modeling and forecasting efforts were only performed on the most highly developed systems in a few offices.

The Mississippi flood of 1993 taxed the limits of the WCDS and became the impetus for development of CWMS. In the mid 1990's, representatives from Corps water control offices around the country met and defined the requirements, then later, the design of CWMS. The design included using commercial and other existing software, as well as the development of new software. Oracle was selected as the relational database of record, and HEC-DSS as the working database for model interaction. Several existing programs for data decoding, translation, and validation were chosen for data processing, while the HEC-HMS hydrologic modeling program and HEC-RAS hydraulic modeling program were selected for simulation programs. A substantial amount of new software needed to be developed, including control and data processors, HEC-ResSim, a reservoir simulation and operations program, and HEC-FIA, a flow impact analysis program.

DESIGN

CWMS is designed using a networked client-server architecture. The server programs, which run on Sun Solaris workstations, acquire, process and store data, and execute the simulation models. CWMS clients, which run on Windows NT computers or Solaris workstations, provides system controls as well as data visualization and model interface functions. This design allows a centrally located database for each office to support sharing of models and modeling results. The use of PCs for clients allows users to access the system from their individual offices or from remote locations, such as from home, if their office becomes inaccessible. The Java programming language was chosen for development because of its platform independence and its rich library of tools, especially in network functionality.

CWMS is comprised of five major groups of programs, as shown schematically in Figure 1. The Data Acquisition (DA) group receives and processes incoming real-time data. The Data Base (DB) group stores and retrieves data in the Oracle relational database. Data Dissemination (DD) delivers data, text and graphics products to users, primarily through Web technology. The Flow-Stage Forecasting (FSF) component is comprised of several engineering models that perform the forecasting of future runoff and project operations scenarios for decision support. The Control and Visualization Interface, or CAVI, enables the user to perform CWMS command and control functions, execute models, visualize data, system status, and outputs.

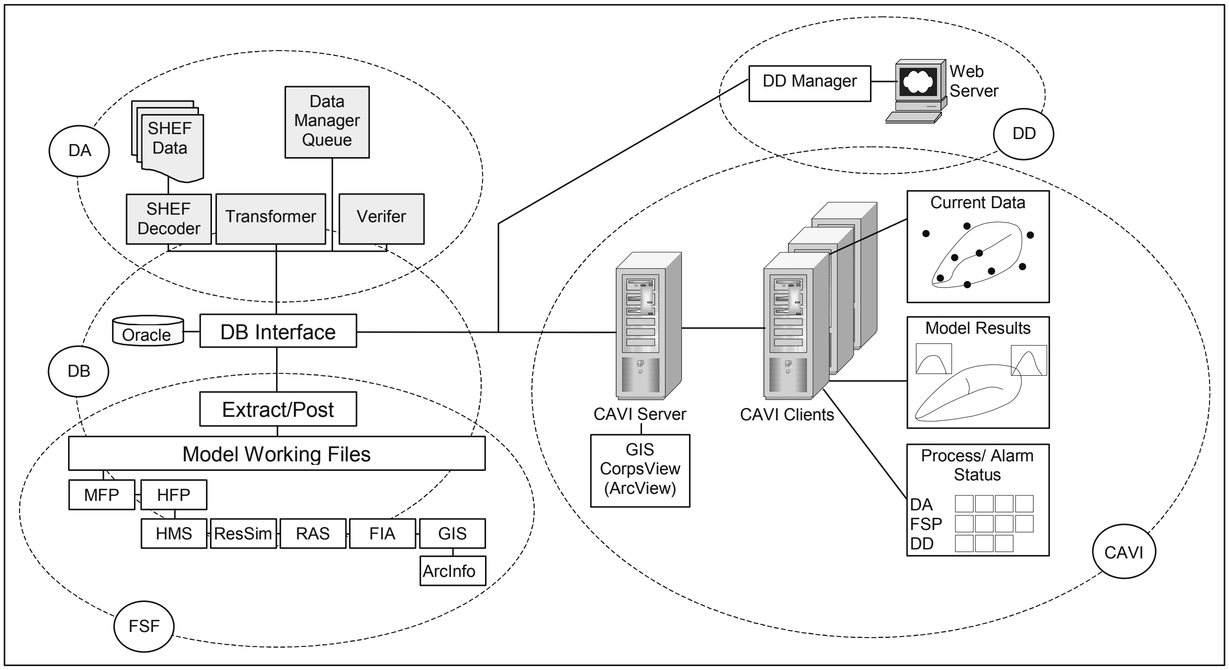

Figure 1 - CWMS Schematic

<u>CWMS Interface:</u> The CWMS CAVI client oversees and controls the operation of the functional modules. The CAVI provides the linkage between incoming data feeds, observed data, models, computed data, operating constraints and the user. It includes mechanisms to: evaluate the quality of incoming data; visualize information in time and space; facilitate primary modeling parameter adjustments; control and execute models; and compare the results of different modeling scenarios.

The CAVI display (Figure 2) contains active icons representing gauges, computation points, and other locations of interest. The icons can display time series data in a "thumbnail plot", a "color bar", or a graphic form. By selecting one or more icons, a user can display two dimensional plots or tables of data represented by those icons. The display can also contain vector or raster maps or images to provide a geospatial context. The raster layers can include animated sequences of precipitation data from NEXRAD or other sources.

CAVI functions are grouped into modules, corresponding to different water management tasks. These are the Data Acquisition Module, the Data Visualization Module, the Model Interface Module and the Watershed Setup Module. Each has a specific set of commands that are accessed through menus, toolbars, scripts and from the context menus associated with the schematic elements displayed in the interface.

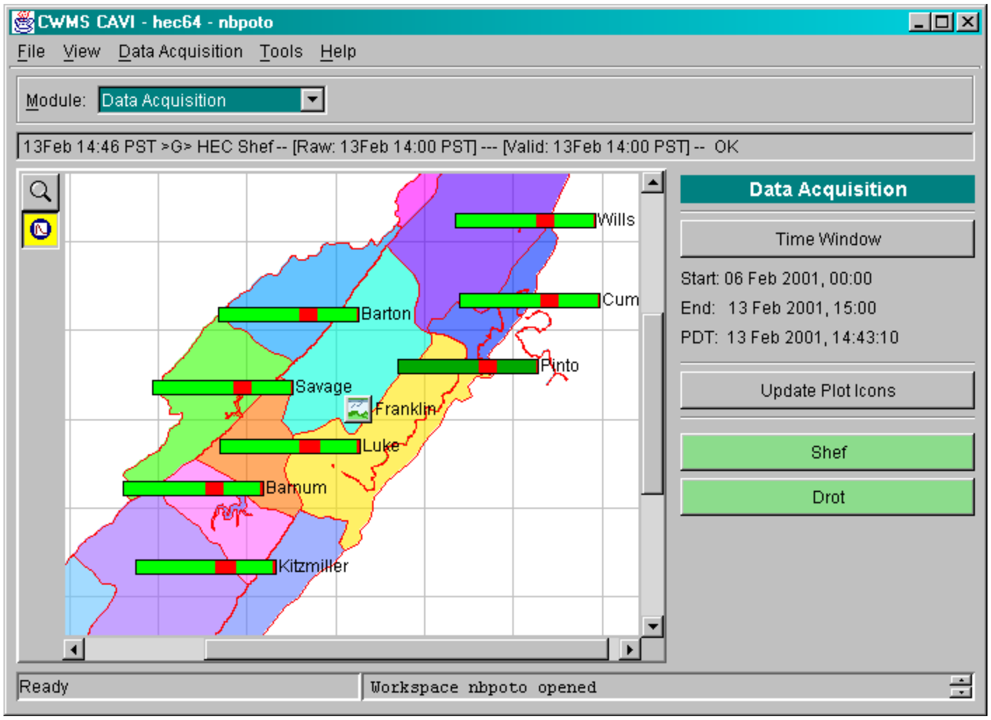

Figure 2 - CAVI Data Acquisition Module

Data Acquisition: Data is collected from field data collection platforms via GOES satellite, NWS AWIPS, line of sight radio, and other sources. The data from each feed is parsed and transformed into engineering units, automatically validated, and stored in the Oracle database. Water Control staff review the status, quality and validation results of the incoming data. Quality color bar icons, as depicted in Figure 2, represent the status and quality of various key data sets for a user-specified time span, such as the past week. A quality color bar represents the variation through time of the quality of data, as determined by a validation program. Graphs and tabulations of data marked questionable or erroneous are shown to authorized users in the "Validation Editor", as depicted in Figure 3, who can edit or accept the data.

Data Visualization: The "Observed Data Visualization" module of the CAVI (Figure 4) is intended to allow the engineer to visually evaluate the hydro-meteorological state of a watershed. The Data Visualization module background consists of an outline map of the watershed and NEXRAD precipitation radar images, which may be animated to show storm movement. If NEXRAD data is unavailable for a particular watershed, a gridded interpolation of precipitation from gauge measurements can be displayed instead.

In the foreground are geo-referenced icons, representing specific data at locations of gauges, as shown in the figure. The icons are typically in the form of a "thumbnail plot" or "threshold color bar". A thumbnail plot is a one-inch square miniature plot of data for that location, while a threshold color bar represents a comparison of data values to threshold value over time by colors. For example, in a threshold stage color bar, green may represent normal stages, yellow warning stages, and red flood stage. Selecting an icon with the mouse generates a full size plot of the data.

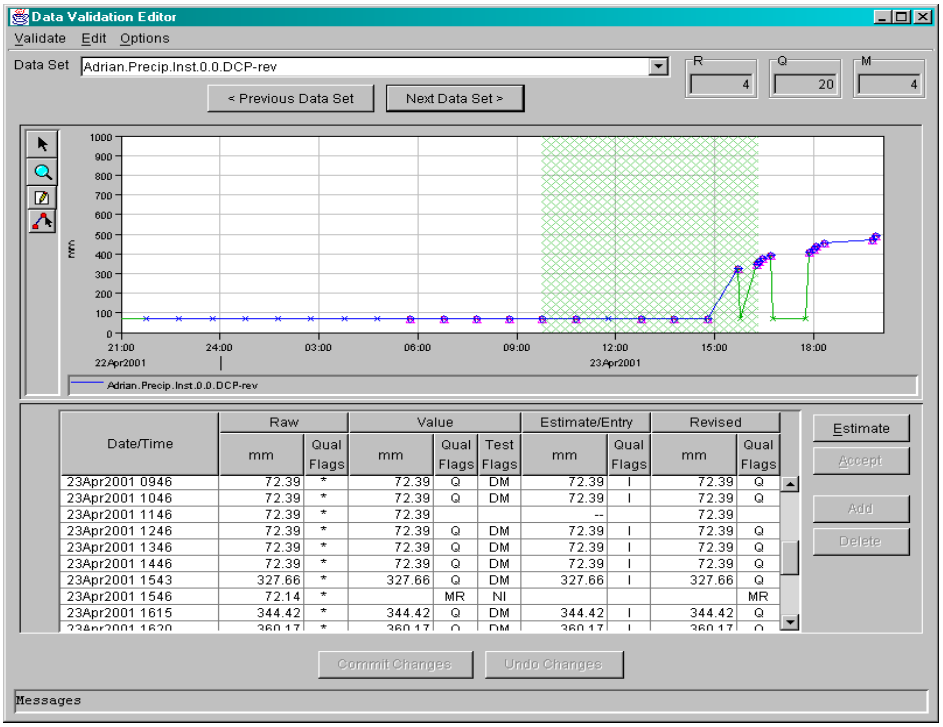

Figure 3 - Data Validation Editor

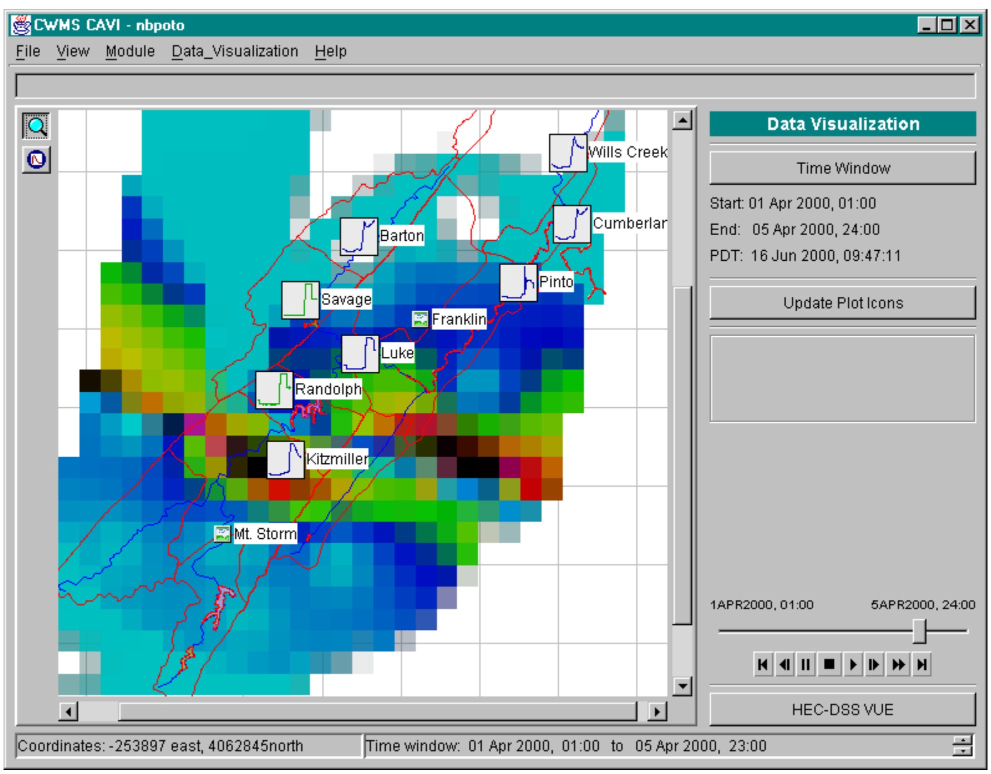

Figure 4 - CAVI Data Visualization Module

MODELING INTERFACE

The modeling component of CWMS allows the water control manager to make short-term (typically a few days or weeks) forecasts of hydrologic conditions in the watershed. CWMS provides an integrated suite of generalized modeling programs that represent different hydrologic aspects of the watershed. CWMS currently includes the following models (listed in sequence of execution for a typical watershed):

- MFP, a simple meteorological model
- HEC-HMS, a hydrologic rainfall-runoff model
- HEC-ResSim, a reservoir operations simulation model
- HEC-RAS, a river hydraulics model
- HEC-FIA, a flood impact economic analysis package
- CorpsView, an ArcView based GIS interface

Other simulation programs can be added to the sequence, or used in place of the ones distributed with CWMS. Each of these programs can run independently, but in CWMS they are combined to provide a comprehensive watershed forecast that can include flow rates, stages, operation plans, economic impacts, and actions to be taken to mitigate the effects of flooding.

CWMS does not require the full sequence of models to be used at all installations. The number and sequence of models is configurable as part of the setup for each office. For example, the Corps's Northwest division office in Portland, Oregon receives hydrologic flow forecasts from the National Weather Service instead of producing their own, so they do not run MFP or HEC-HMS in their forecasts. The New Orleans district does not operate any reservoirs, and currently runs only a HEC-RAS hydraulics model of the lower Mississippi River through CWMS.

Scenarios: To support decision making in uncertain conditions, the user can simulate more than one scenario and compare their results through a single interface. Typical scenarios might include several different gate-setting plans for dam operations and several precipitation forecasts, which will give rise to several different flow rates through the watershed. The user can, for example, combine any of the dam operating plans with any of the precipitation forecasts to see if those plans will produce acceptable results under a variety of flow conditions. This kind of complex comparison requires the ability to run several alternative versions of individual models, and to combine those individual model alternatives to build complete forecasts.

Two key elements make forecasting multiple scenarios with multiple models possible: a common database shared by all the forecast models and a common user interface that allows the operator to create and adjust alternative parameter sets for each model and combine those individual alternatives into comprehensive forecast scenarios.

Modeling Database: The common database is HEC-DSS (Charley, 1995), which contains time series data extracted from the main CWMS database when the forecast is initiated. Each model then extends the observed data into the future, building on the results of the preceding model in the simulation sequence. The results of each forecast scenario are identified separately in the HEC-DSS database and can be compared with observed data for calibration, or with the results of other forecast scenarios for decision support. By keeping the forecast modeling database separate from the database of record, CWMS models are unaffected when new data is posted to the record database.

SIMULATION MODELING

The CAVI's model interface module allows the user to adjust the parameters of each model individually and save those adjustments for use in later forecasts. A saved set of parameter adjustments is called an "alternative" for that model. In order to run the models, the user must select one alternative for each model to be executed. The combination of individual model alternatives into a set for execution is called a "forecast alternative." The user can run several forecast alternatives and display the results of any or all of them in combination to make comparisons and plan operations. A description of these models follows.

Meteorology: The Meteorological Forecast Processor, or MFP, processes future precipitation scenarios, which can vary through both time and space, and can be derived from National Weather Service QPFs or by manual entry. For manual entry, areas of the watershed are divided into "zones", and the amounts and timing of future rainfall are entered into MFP for each zone. Based on these inputs, MFP generates precipitation grids to be read by HEC-HMS for hydrologic modeling. The amount and timing of future rainfall is typically varied to produce various "what if?" scenarios.

Hydrology: The Hydrologic Modeling System (HEC-HMS) computes the hydrologic forecasts. HEC-HMS uses the ModClark model for rainfall/runoff transformation from distributed rainfall data, provided in a gridded format, such as NEXRAD precipitation data (Smith, 1999). ModClark is an adaptation of the Clark conceptual runoff model for unit hydrographs. In the ModClark model, a grid is superimposed on the watershed to form a collection of contiguous grid cells, each approximately 2 km x 2 km. Each cell is assigned a travel time index, which represents the travel time from the cell to the outlet. Rainfall is applied to each grid cell and infiltration losses are subtracted. The excess rainfall is lagged by the grid cell translation time and routed through a linear reservoir model. The cell hydrographs are accumulated at the outlet and added to a base flow component to compute the total subbasin hydrograph.

Loss and base flow parameters for groups of subbasins are adjusted to match observed conditions through the CAVI. This adjustment may be accomplished through parameter optimization routines using observed flow, or from manual adjustment. Where they are available, observed flows are substituted in the hydrographs for calculated flows. The results from HEC-HMS are flow hydrographs at points in the watershed where flows are not controlled by dams or other structures.

Reservoir Simulation and Operations: Reservoir operations are modeled for various runoff scenarios with the HEC-ResSim program. HEC-ResSim uses the inflow and local downstream hydrographs generated from HEC-HMS, along with user-defined operating rules and scheduled releases, to simulate reservoir operations for the various runoff scenarios. Through the CWMS interface, users can manually set release schedules to take precedence over the operating rules, although it will not change physical constraints on releases or reservoir capacities. HEC-ResSim computes pool elevation and storage time series, and flow hydrographs at control structures and downstream locations. "Holdout" hydrographs are computed automatically for project benefit analysis.

Hydraulics: River hydraulics are computed with HEC-RAS, which will perform steady or unsteady flow modeling. From the hydrographs produced by HEC-HMS or HEC-ResSim, HEC-RAS computes water surface profiles and stage hydrographs. When used in conjunction with ArcInfo through CWMS, inundation boundaries and depth maps are computed, and are viewed through CorpsView, an extension to ArcView. Channel friction factors can be adjusted through the CWMS interface.

Economics and Impact: Economic analysis and impacts are conducted by HEC-FIA, the "Flow Impact Analysis" program. HEC-FIA calculates agricultural and urban damages and project benefits by impact area, and then accumulates them for the system. Project benefit accomplishments are computed as the difference between alternative scenarios, typically the with- and without-projects conditions. Benefits are then automatically or manually allocated among the various projects. The results are displayed by event, by damage category and by project for the watershed using any of the specified boundary data. Output reports summarize information on damage, area, number of structures, and population flooded and project accomplishments for various alternatives. "Action Tables" provide a list of actions to take, and when they should occur, based on forecasted stages.

Supplemental Models: CWMS supports other modeling programs through a mechanism that identifies them as "supplemental programs." This allows a user to insert additional modeling programs into the model sequence or to replace a default model with a different model. For example, the CASCADE model—which was developed for unsteady-flow hydraulic routing between lock and dam operations on the Ohio River—replaces both HEC-ResSim and HEC-RAS in the CWMS implementation at the Corps's Great Lakes and Ohio River division office in Cincinnati. The Albuquerque office uses the USGS's Modular Modeling System (MMS) (Leavesley, 1996) in conjunction with CADWES's RiverWare (Zagona, 1998) program through HEC-DSS, to cooperate with other agencies in their area. Although supplemental models can be triggered by the CAVI, the CAVI is not able to provide as much run-time control for as it does for the models provided with the system. Installations that use supplemental models must provide a script that can execute the model in response to a call from the CAVI and a means for their results to be stored in HEC-DSS.

CWMS STATUS

Deployment: The CWMS deployment to 42 Corps water control field offices began in September 2001, and was completed by December 2002. Each office required about six months time for deployment activities. Deployment begins with a training session on CWMS, identifying and setting up data feeds, and selecting a deployment watershed. Subsequently, the various models for the watershed must be built, calibrated, tested and integrated into CWMS. Activation of CWMS commences with on-site training and daily operations of the models. After the initial deployment, offices will continue building models and setting up CWMS for the remainder of the watersheds in their district.

Releases: The initial test version of CWMS was fielded in September 2001. Errors and modifications requested by offices with that version were incorporated into the software for the Version 1.0 release in March 2002. Version 1.1 was released in February 2003, with subsequent major releases planned annually.

Because the initial development of CWMS has been completed, the project has entered a "betterments" phase. Funds have been allocated to improve the capabilities of CWMS, as well as maintain it, throughout its life cycle. The Version 1.1 release included better data acquisition processing, an enhanced 2-D graphics capability, full accesses to CAVI capabilities through Jython scripting, as well as inclusion of the initial release of HEC-DSS Vue, a graphical user interface for modeling data in HEC-DSS files, and the initial release of HEC-ResSim.

Current work underway for a January 2004 release includes the installation of a Continuity of Operations Plan, or COOP, at the Corps' Central Processing Center in Vicksburg, Mississippi, and implementation of security measures. The COOP site will contain a "hot backup" of all data, models and other information in CWMS, as well as national data feeds, so that an office can instantly switch to that location should their office become inaccessible. Improvements to CWMS for this version also include access of parameters for the recently added snowmelt algorithms in HEC-HMS through the CAVI, storage and use of rating tables in the Oracle database, improved client-server network access, and complete ResSim hydropower operations.

Future enhancements include the use of advanced continuous soil moisture accounting algorithms, and the use of probabilistic information throughout the models. This would be coupled with a scaling capability for models, so that the impact of a specific reservoir operation or forecast scenario could be evaluated on a system-wide basis as well as for a limited local area. Plans also include a complete implementation of checking data entering the system and issuing alarms, which would notify operators via email, pager, and various other means. Web based data entry and better data dissemination capabilities are also anticipated to be included in a future version.

Lessons Learned: Both HEC and the water control community that it serves have learned a lot from the experience of deploying CWMS to the 42 district and division offices where it is now running. Some of those lessons have to do with software design and implementation, and others have to do with building a community of water controllers in the Corps.

For the software development, it became apparent that one size doesn't fit all. Corps offices interact with other federal agencies, state governments, municipal governments, governments of other countries, private power generators, quasi-government river authorities, and other cooperating entities too numerous to identify. In some places this means that hydrologic data comes to the Corps in an unusual format, which must be translated before CWMS can store it. In others, this means that a particular modeling program must be used for forecasting. Reports must be generated to conform to interagency agreements. Units must be converted to metric for agencies outside the United States. CWMS must be flexible enough to accommodate all these variations, or water controllers won't use it.

There are a variety of components in CWMS, with each component having a different configuration file that has to be set for an initial installation. Occasionally, the information required by one component is required by another as well, which can lead to redundancy and inconsistency. Each update to CWMS has cleaned up some part of the system, but clearly we have a long way to go. The configuration files need to be consolidated and information in them needs to be presented to the administrator in a clear and concise manner through a graphical user interface.

Additional modeling components are needed for integration into CWMS. The interface must be continually updated to incorporate new modeling feature in programs from HEC and other developers. Presently HEC is expanding CWMS ability to model snow processes in hydrologic forecasts, and lock and dam operations in river hydraulics.

CWMS development has organized a Corps-wide network of water control offices and developed a stronger community than had existed before. From its inception, CWMS has called on the Corps's water controllers to contribute to program design, to set priorities for program enhancements, and to test the system components as they are developed. The CWMS project created a CWMS user representative group (the CURG) and a CWMS advisory group, now called the CWMS Configuration Control Board. These groups were created to guide CWMS development through meetings and telephone conferences, and they have performed that task well. They have also become a forum for water control concerns beyond CWMS. The meetings, e-mail exchanges and telephone conferences have allowed solutions developed for problems at one office to be shared Corps-wide. The rapid propagation of the DECODES program is an example of this community in action. The water control community should continue to develop through sharing of SOPs, scripts, and other problem solutions.

CONCLUSION

CWMS provides an comprehensive integrated system for the Corps of Engineers to collect, analyze, and model real-time data for decision support of water control operations. A full range of modeling software allow engineers to evaluate operational decisions for reservoirs and other control structures, and to compare the impacts of various "what if?" scenarios. CWMS has been designed to allow the engineer to concentrate on the hydrology and alternatives of an event, instead of the computer aspects of processing data and running programs. CWMS deployment to Corps offices across the country was completed in December 2002. Maintenance and limited betterments programs are in place to maintain and improve CWMS throughout its life cycle.

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